Intrinsic superconducting phases in $La_{2-x}Sr_xCuO_4$ single crystals at magic dopings

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Collaborators

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NSFC and the National Basic Research Program of China

Outline

- The magic doping at 1/9 is missed in the most phase diagrams
- Intrinsic superconducting phases at magic dopings with p = 1/16 and 1/9 and their peculiar features
- Evidences from literatures support magic dopings at 1/16 and 1/9
- Composite charge model
- Summary

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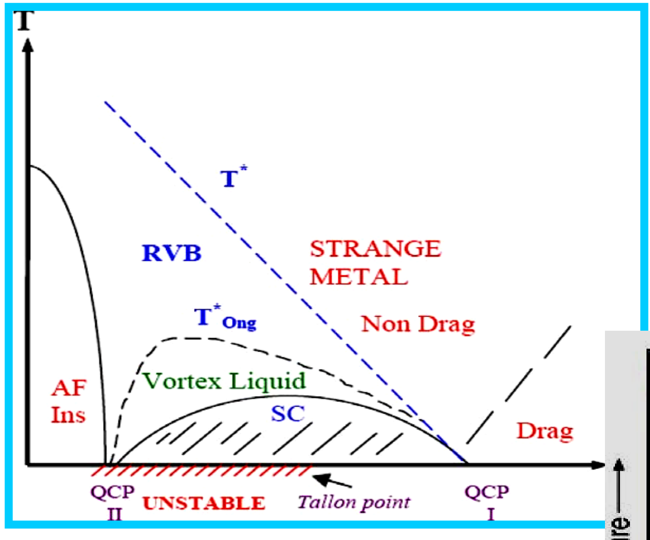
Phase diagram is important to the mechanism Different experimental probes give phase diagrams with difference in details

LSCO, transport, magnetization, P.G. Radaelli et al (1994) ; T. Nagano *et al*. (1993)
$La_{2-x}Ba_xCuO_4$, Neutron, Fujita, Yamada et al (2012)
Hg1201&YBCO, Transport and others, Barisic, Greven et al(2013)
YBCO, NMR, Wu, Julien et al (2011); Neutron, Chang, Mesot et al (2012); Quantum Oscillations & complementary measurements, Sebastian et al (2012)
…

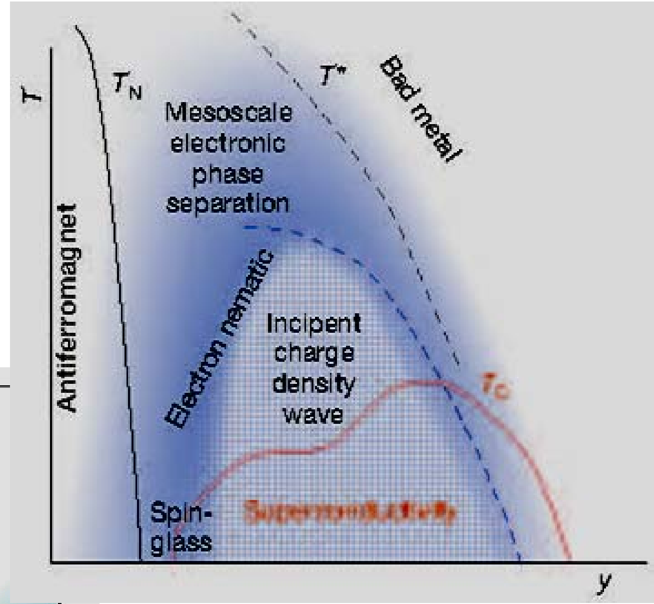
Different models give different sketches

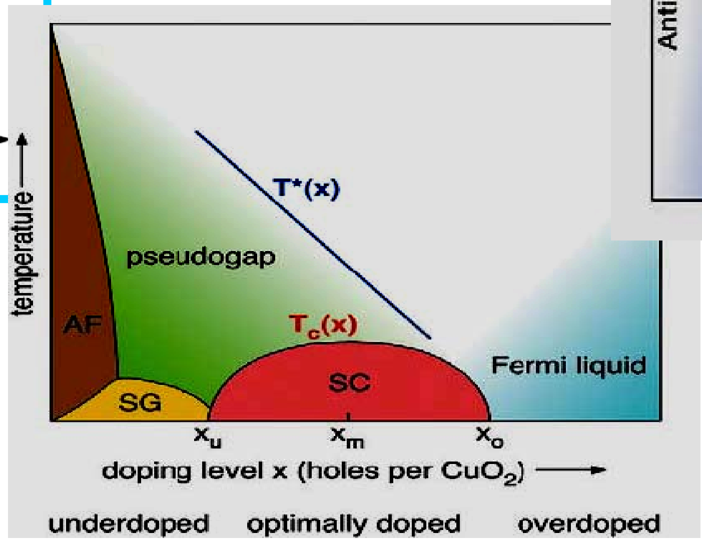
The major is the same, the details are different which imply different mechanism

P.W. Anderson (2007)



Fradkin& Kivelson(2012)

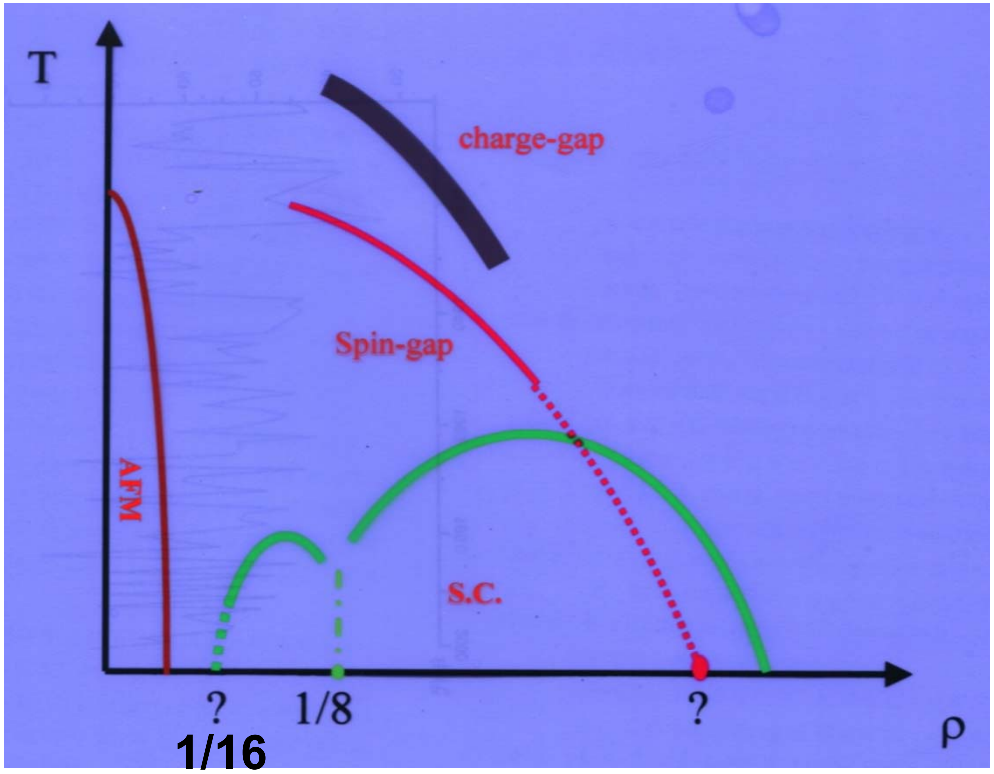




H. Keller, A. Bussmann-Holder,
K.A. Muller *et al* (2008)

Some models notice the existences of QCPs, SDW or CDW thus pay attention to special dopings such as 1/16 or 1/8

However, another magic doping at 1/9 is missed



1/8 anomaly in $La_{1.875}Ba_{0.125}CuO_4$ is observed: Structural phase transition;Tc =0

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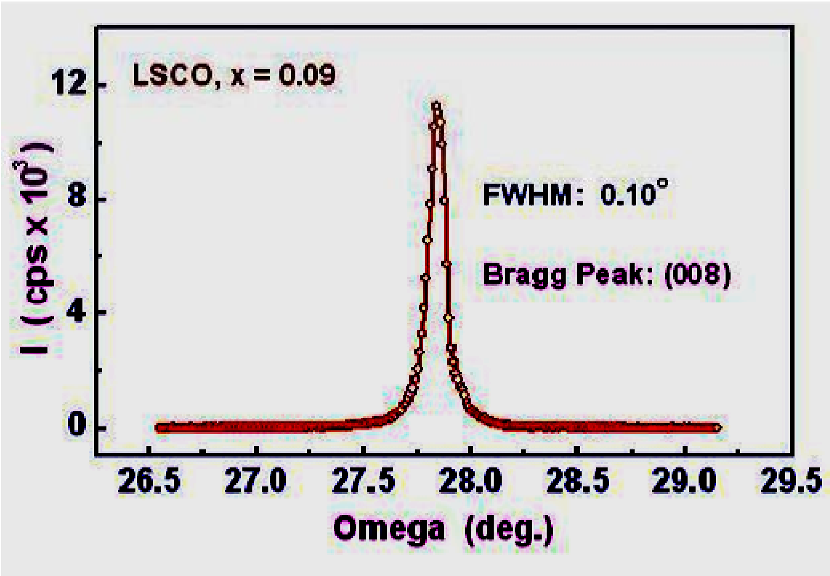
Characterizations of crystal quality

Highest quality of LSCO single crystals!

F. Zhou et al. Supercond. Sci. Tech. 16 , L7 (2003); Physica C 408, 430 (2004)



Double-crystal x-ray rocking curve for x = 0.09 LSCO crystal.

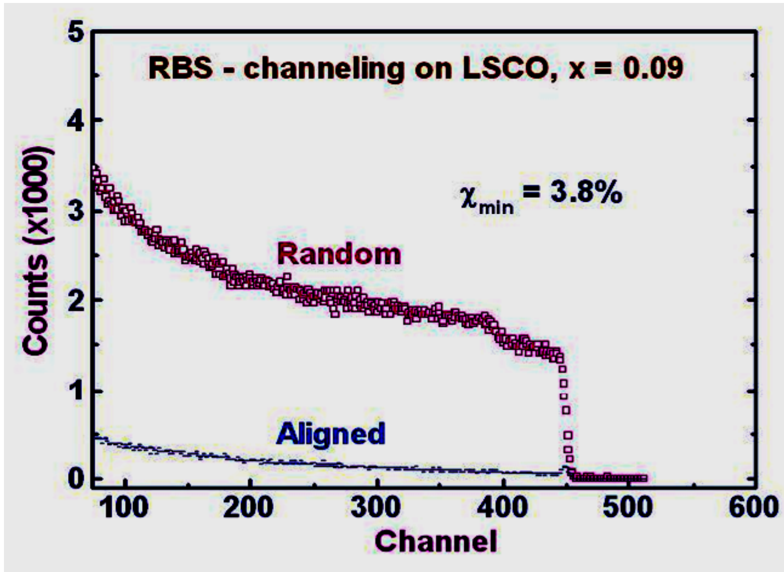
sample surface: 4mm×15mm;

beam slit: 0.5mm×10mm.

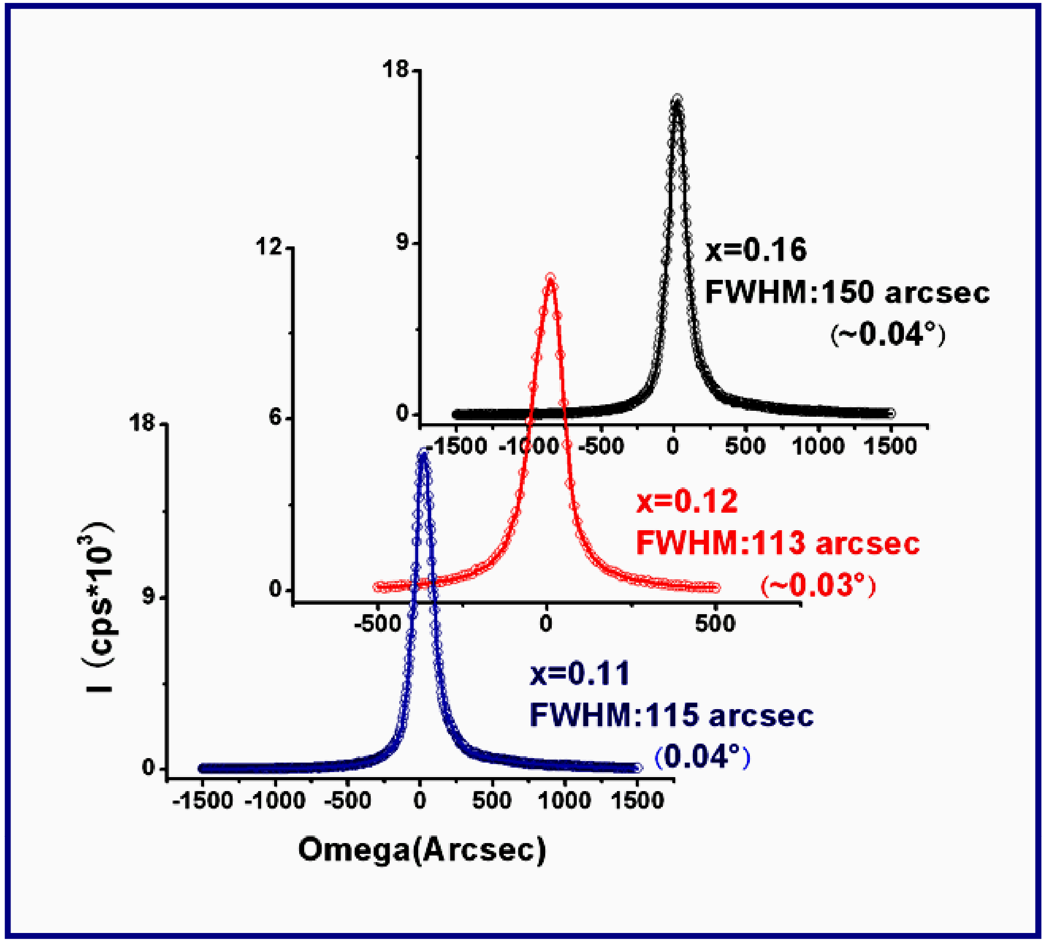
FWHM = 0.10° (one of the best data reported so far for LSCO).

2-MeV $^4He^+$ ions RBS-channeling effect on x = 0.09 LSCO crystal.

minimum yield χ_{min} = 3.8%; very low defect density according to the flat backscattering curve of the aligned spectrum.



Characterizations of crystal quality



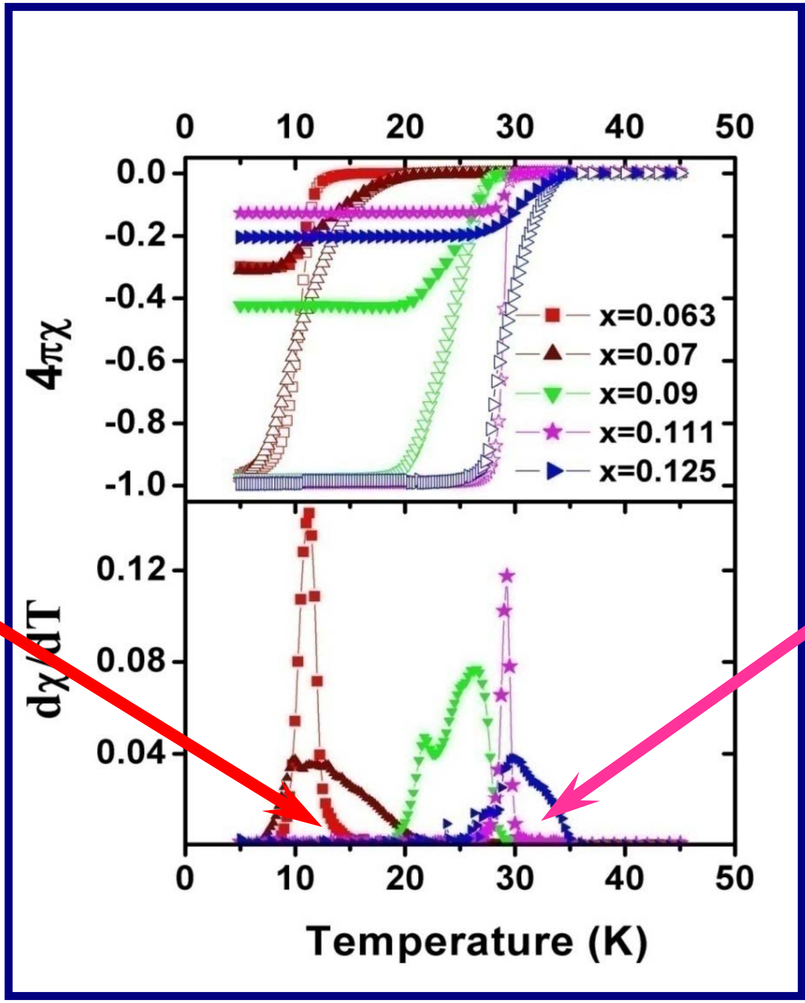
Double-crystal x-ray rocking curve for 3 LSCO crystals.

FWHM = 0. 04°
(the best data reported so far for LSCO)

Magic dopings (1/16, 1/9) in LSCO: susceptibility

Sharp SC transition (15K, 30K) at magic dopings (1/16, 1/9)

T_{C1} = 15K
X ~ 1/16



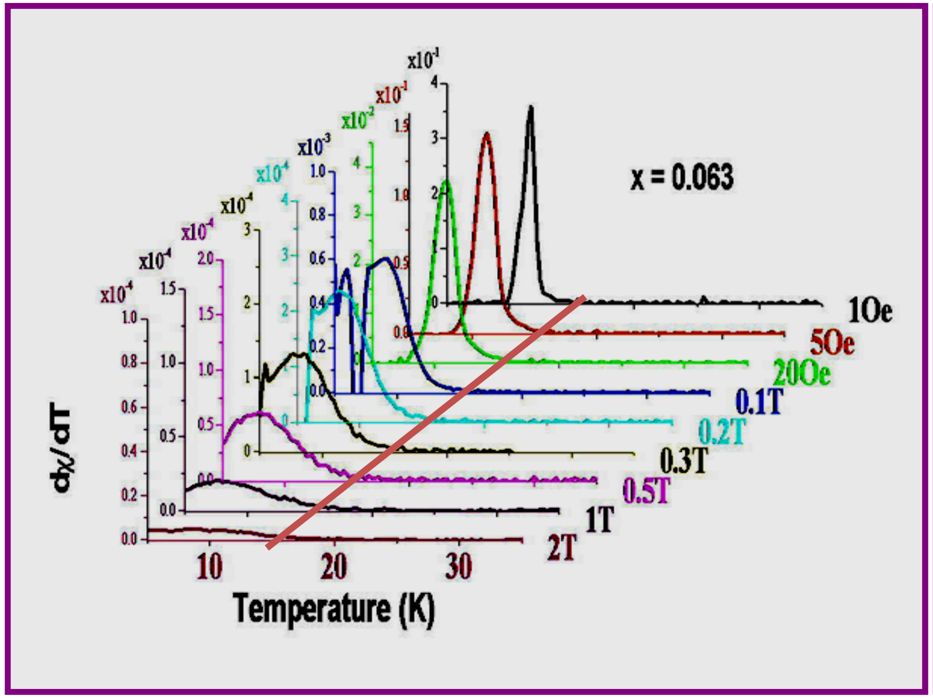
T_{C2} = 30K
X ~ 1/9

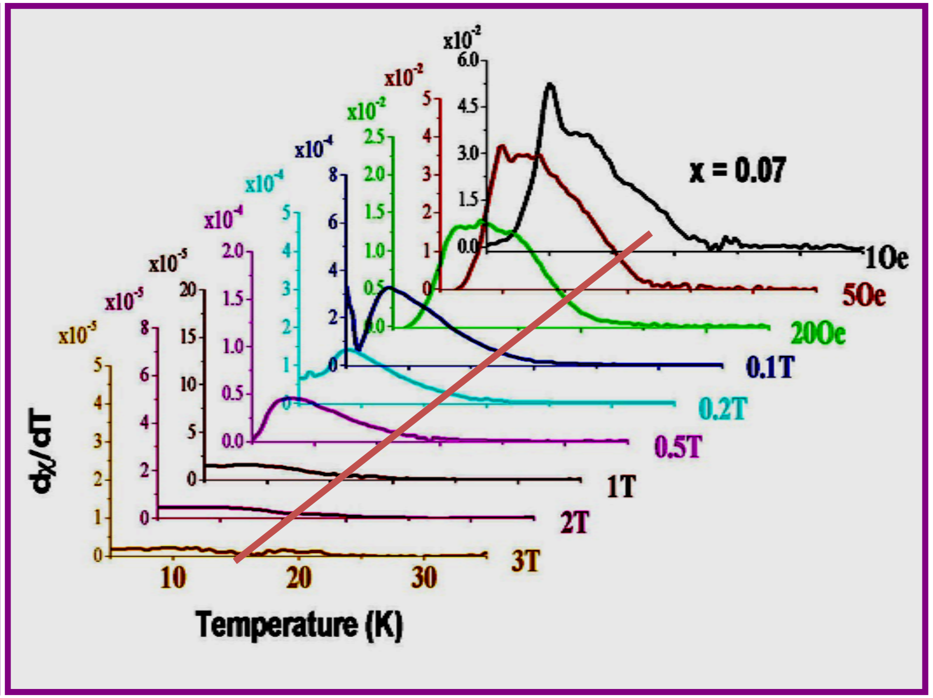
F. Zhou et al, Supercond. Sci. Tech. 16 (2003) L7; Physica C 408 (2004) 430
X.L.Dong, P.H. Hor, F. Zhou, Z.-X. Zhao, Solid State Commun. 145 (2008) 137

Onset T_Cs at magic dopings show 'robustness' in magnetic field

X.L. Dong, P.H. Hor, F. Zhou, and Z.X. Zhao, Solid State Commun.145, 173 (2008)

'robust' 15K -dχ/dT under different fields



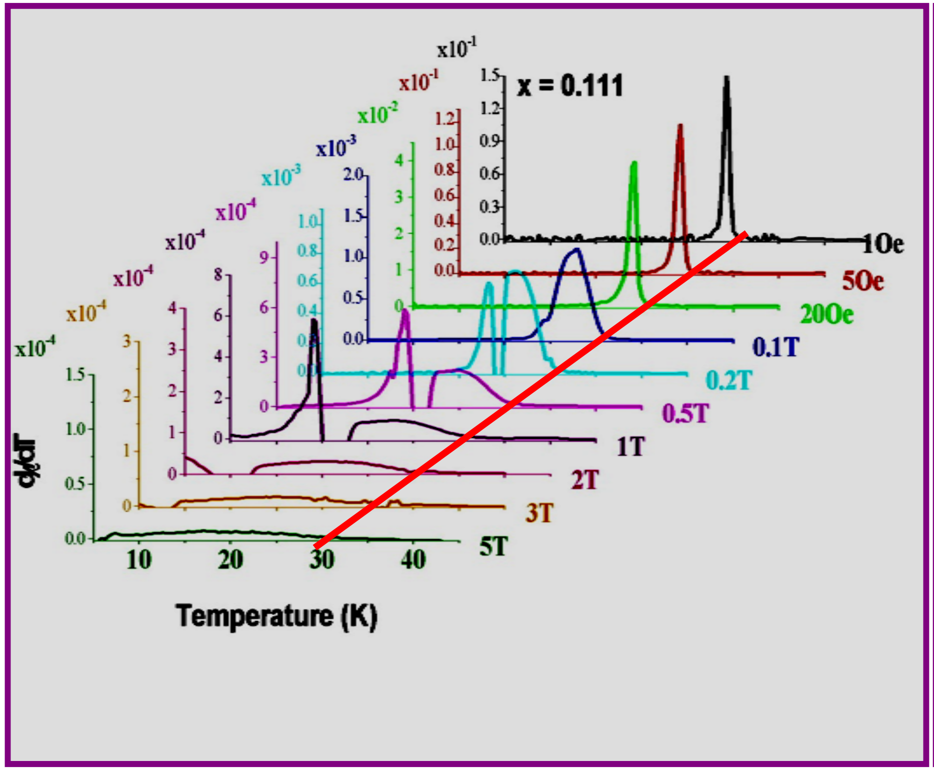


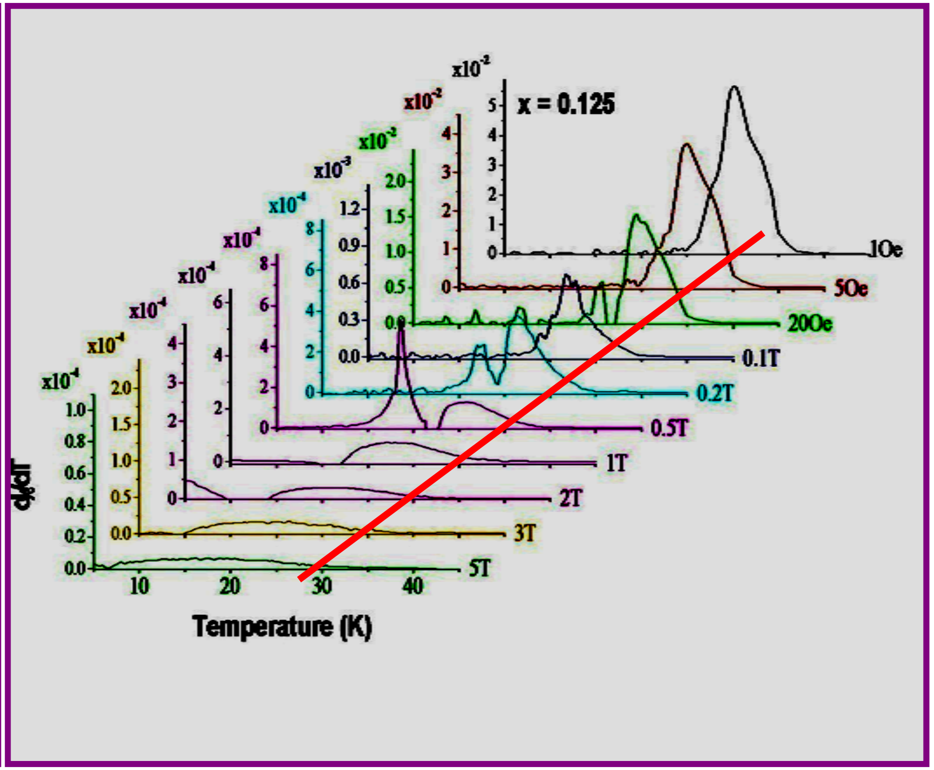
Tc remains at 15 K with field up to 2 Tesla for 1/16 doping ; Tc decreases from 23K to 15 K with field increasing and stays at 15 K when field increases further for 0.07 doping

Onset T_Cs at magic dopings show 'robustness' in magnetic field

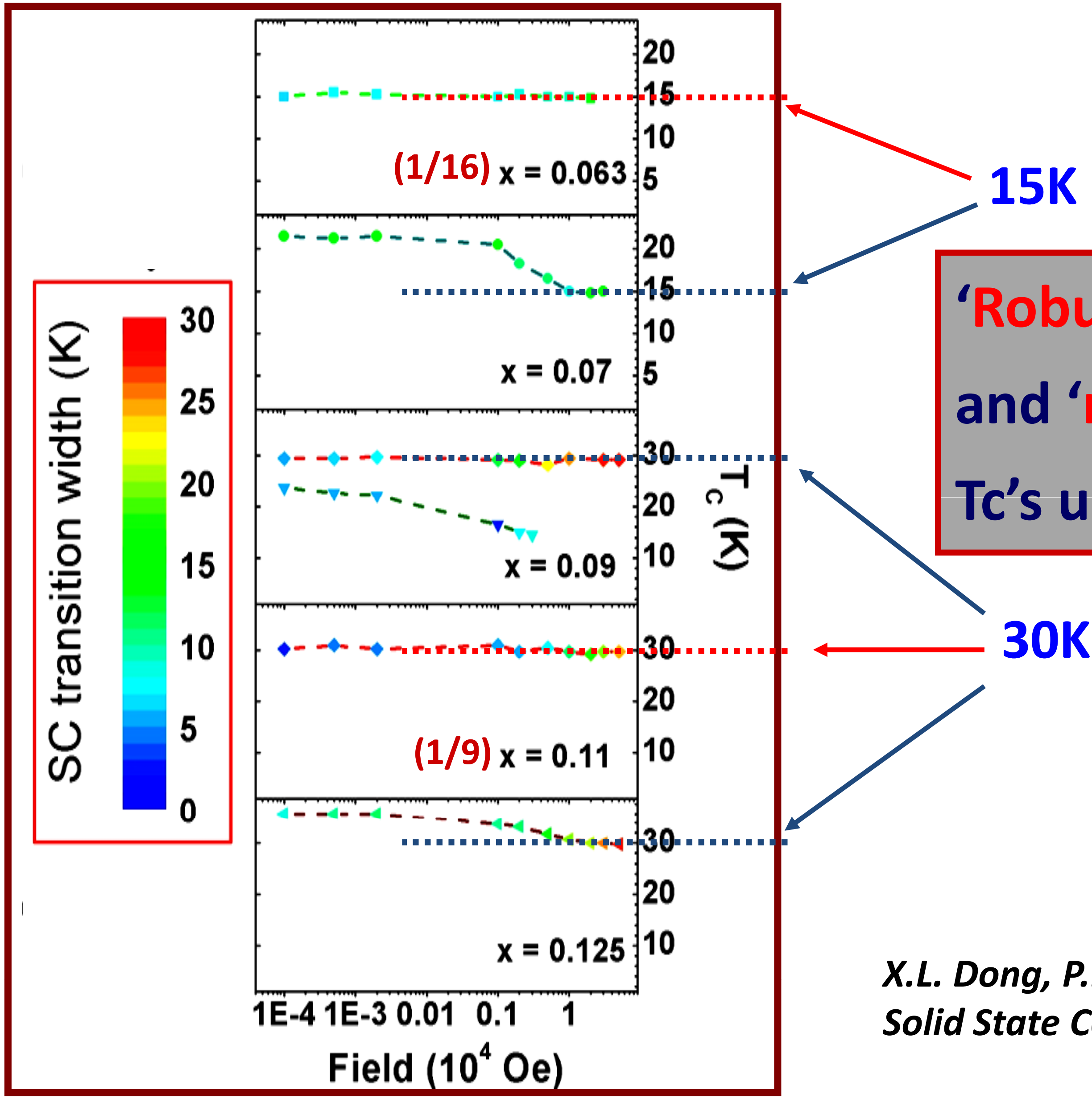
X.L. Dong, P.H. Hor, F. Zhou, and Z.X. Zhao, Solid State Commun.145, 173 (2008)

'robust' 30K -$d\chi/dT$ under different fields





Tc remains at 30 K with field up to 5 Tesla for 1/9 doping ; Tc decreases from 38K to 30 K with field increasing and stays at 30 K when field increases further for 0.125 doping

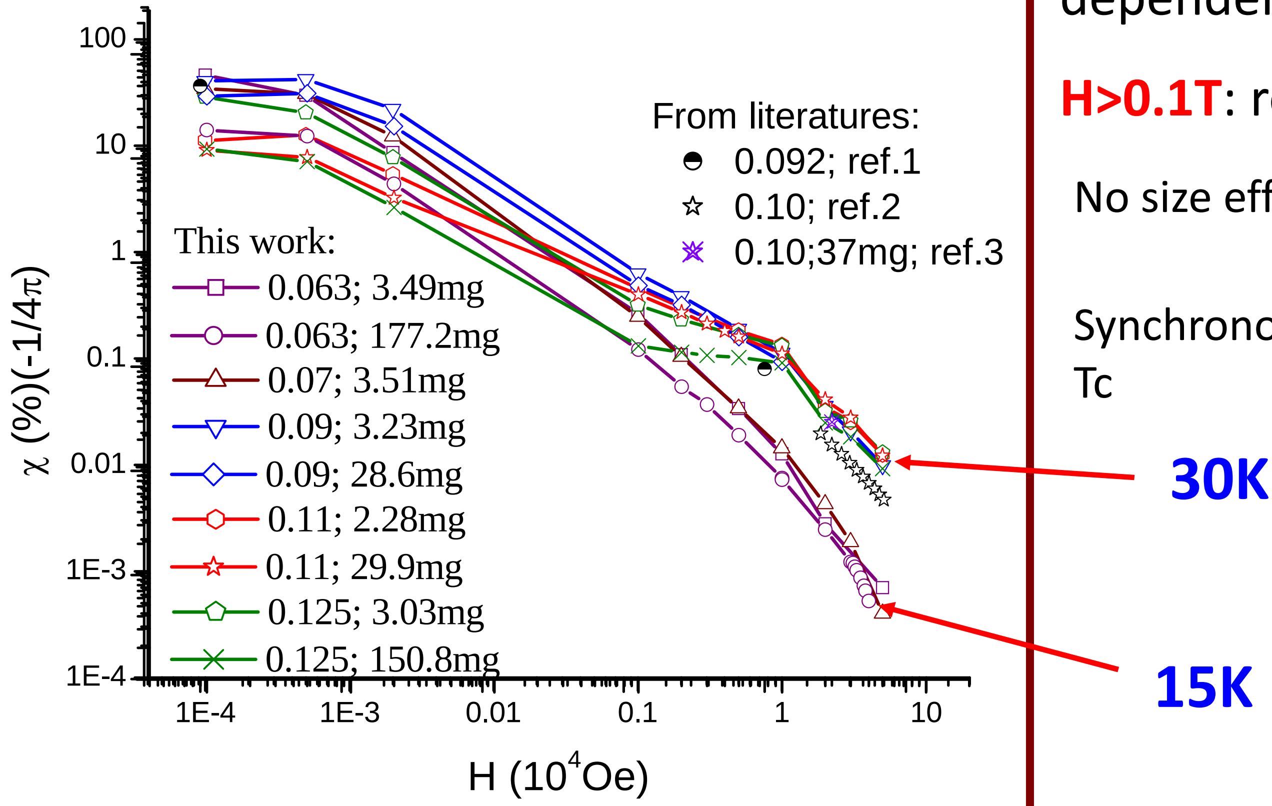


'Robustness' of intrinsic Tc and 'regress' of apparent Tc's under field

X.L. Dong, P.H. Hor, F. Zhou, and Z.X. Zhao, Solid State Commun.145, 173 (2008)

Field-cooled diamagnetic signals ‘regroup’ as that of Tc = 15K and 30K superconductors, respectively

X.L. Dong, P.H. Hor, F. Zhou, and Z.X. Zhao, Solid State Commun.145, 173 (2008)



H<0.1T: shows no monotonic dependence upon doping level

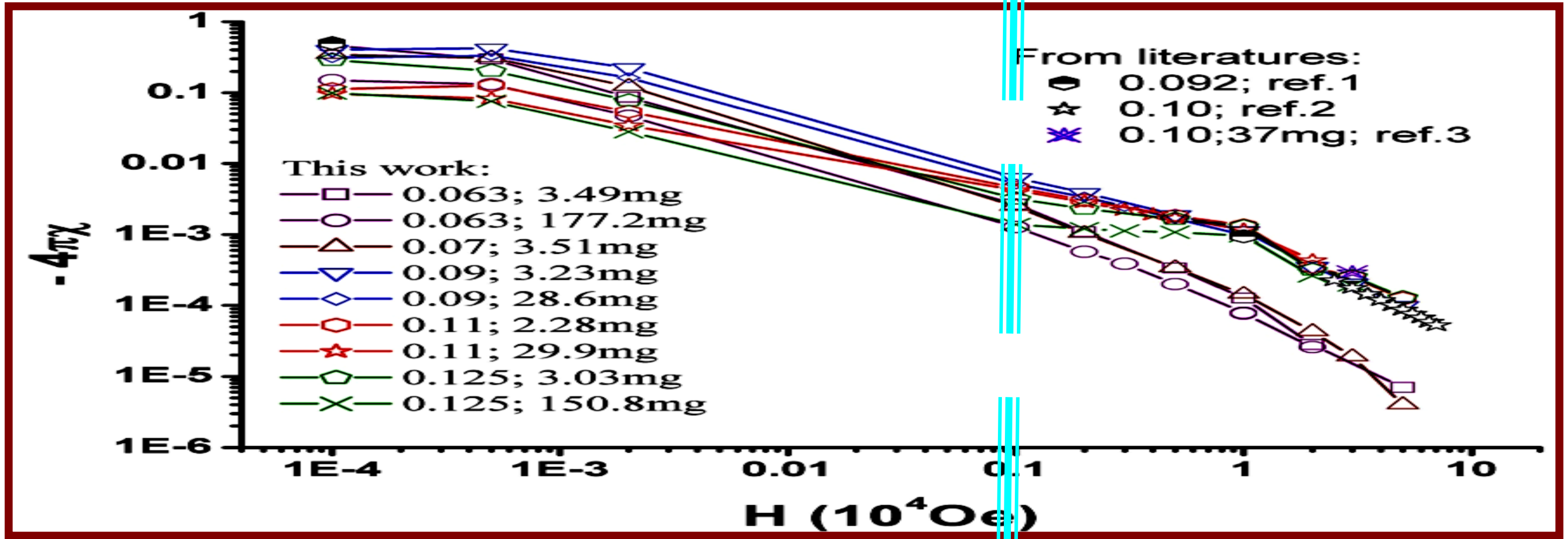
H>0.1T: regrouping starts

No size effects

Synchronous behaviors as that of Tc

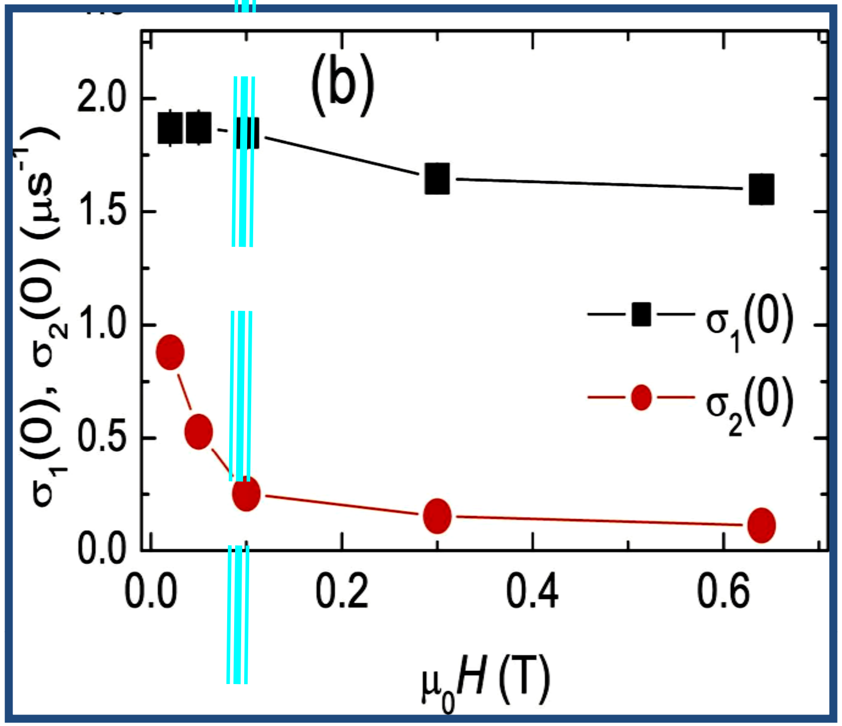
References:

1. **T. Sasagawa *et al.*, PRB 61, 1610 (2000).**
2. **Y.M. Huh *et al.*, PRB 63, 064512 (2001).**
3. **R.Gilardi *et al.*, cond-mat/ 0412471 (2004).**

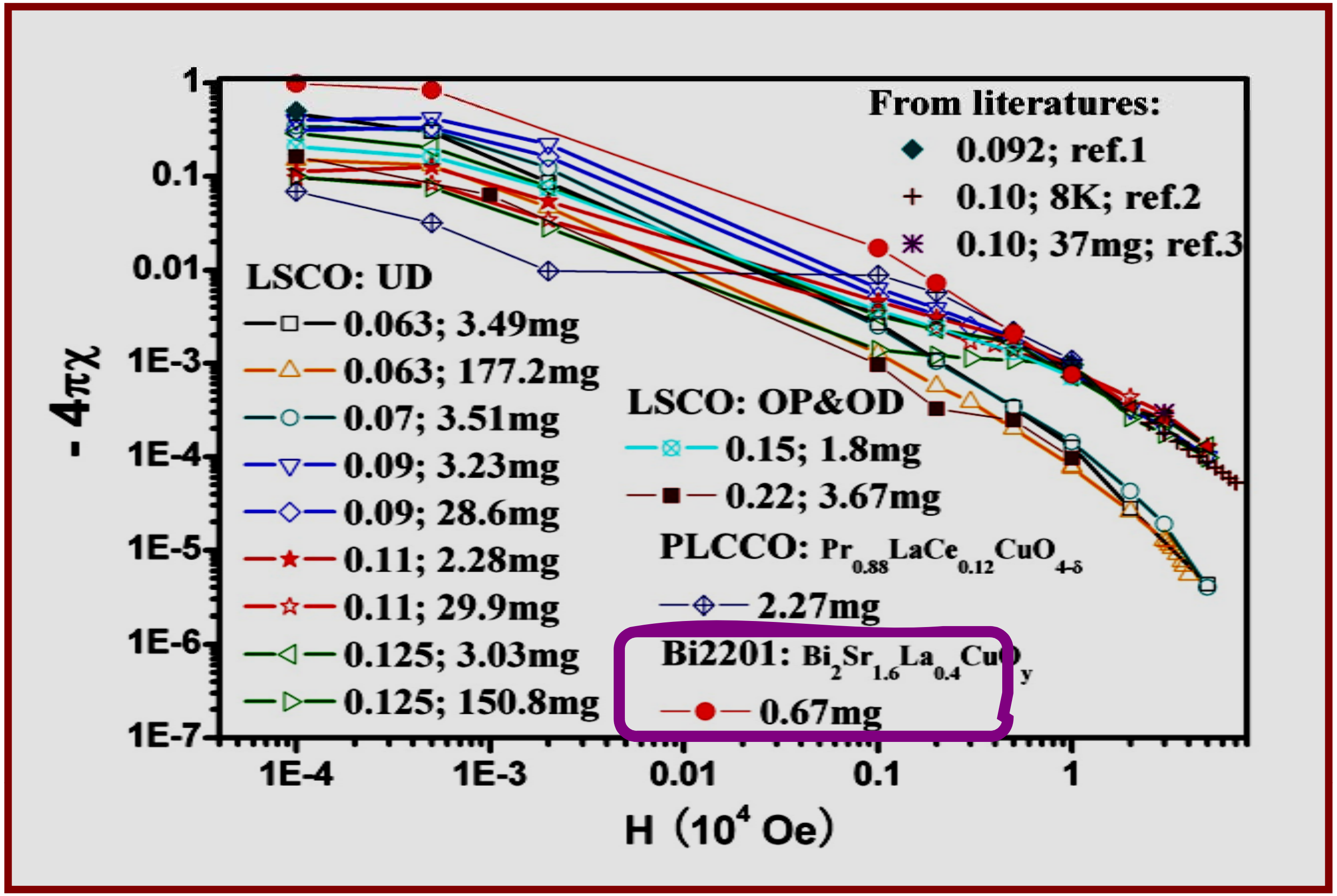


μSR:
s-wave gap decreases rapidly when H > 0.1T.
d-wave gap shows little change under field.

R. Khasanov *et al*, PRL98, 057007 (2007)



To confirm the intrinsic superconducting phase is universal in single-layer cuprates, we examine PLCCO and Bi2201 :
their diamagnetic signals (at 5K) 'regroup' under field, following the same two lines, with no dependence on doping level, dopant or carrier type (unpublished) .

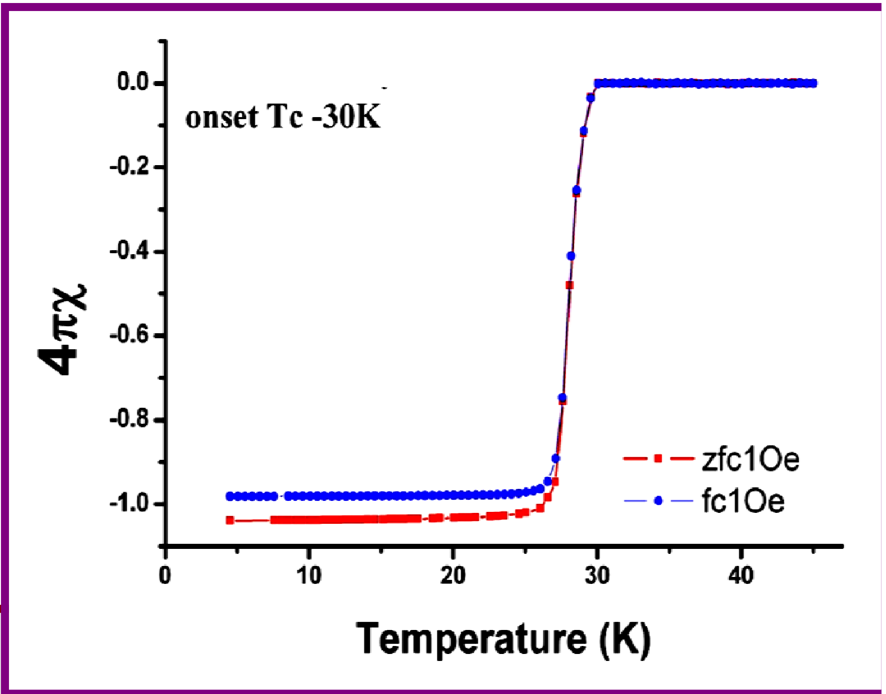


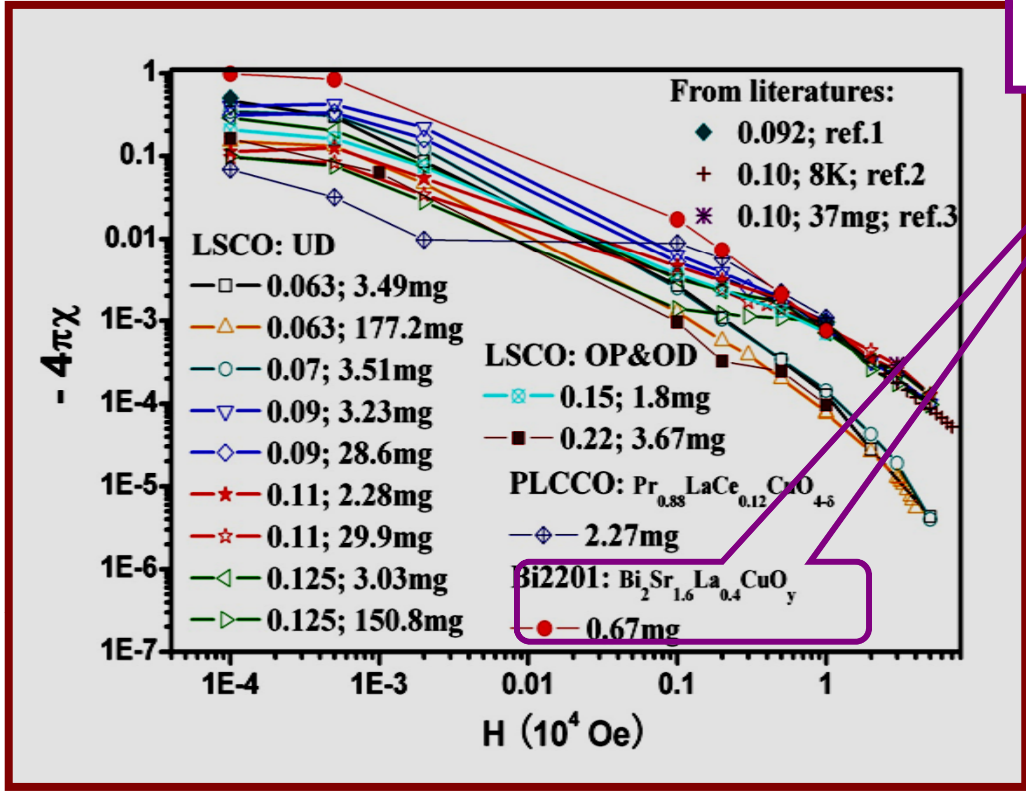
χ-T of La-Bi2201:

T_C = 30K

nearly 100% Meissner

Little difference between ZFC & FC under 1 Oe indicates extremely low disorder



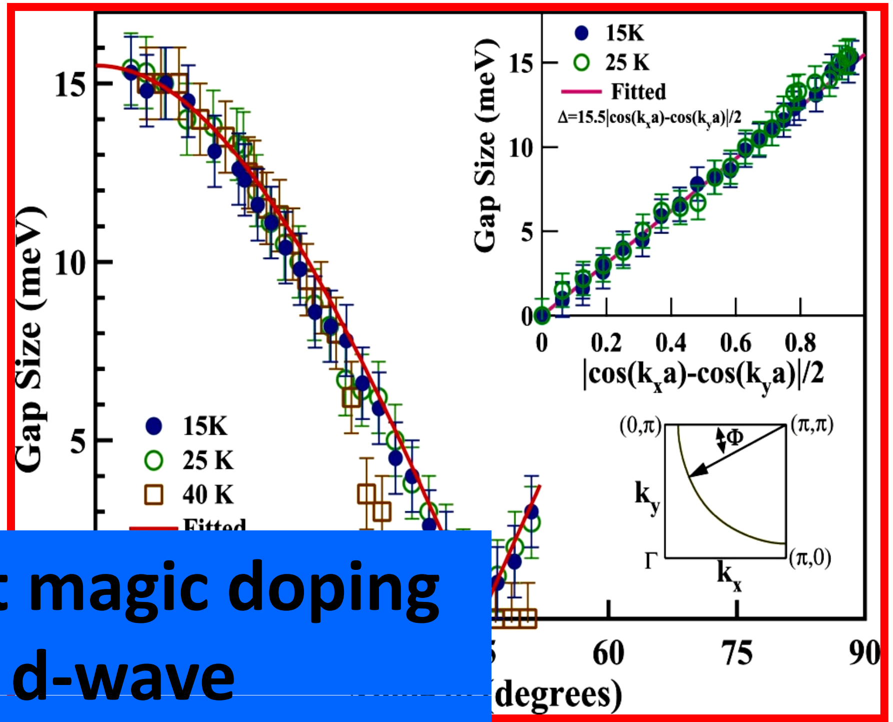


Following the 30K regrouping line

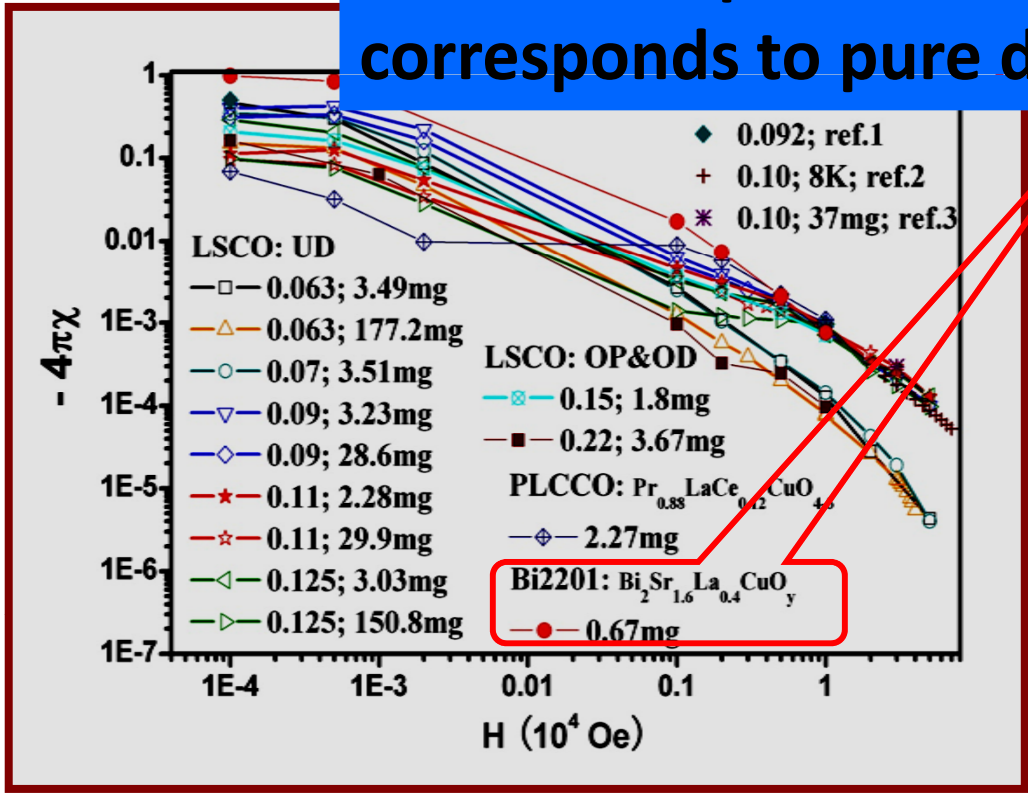
Suitable for ARPES

Laser-based ARPES:
pure d-wave SC gap

JQ Meng *et al*, PRB79, 024514(2009)



Intrinsic SC phase at magic doping corresponds to pure d-wave



ARPES:

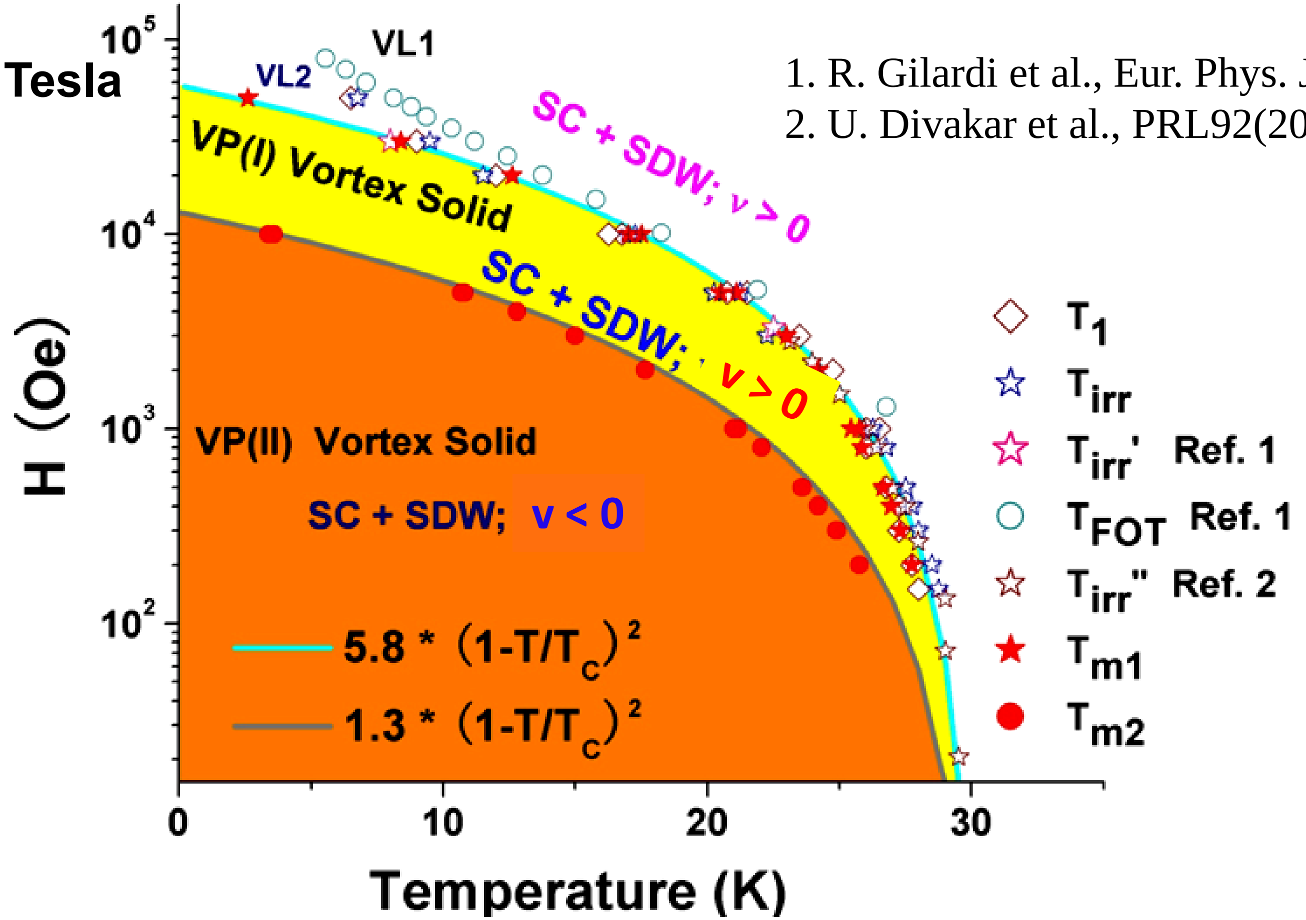
The superconducting gap of La-Bi2201 with Tc of 30K is of a single d-wave one (dx^2-y^2).

Magnetic phase diagram at doping level of 1/9

A new phase boundary is found below melting line

X.L. Dong, P.H. Hor, F. Zhou, and Z.X. Zhao, Solid State Commun.152, 1513 (2012)

< 5 Tesla

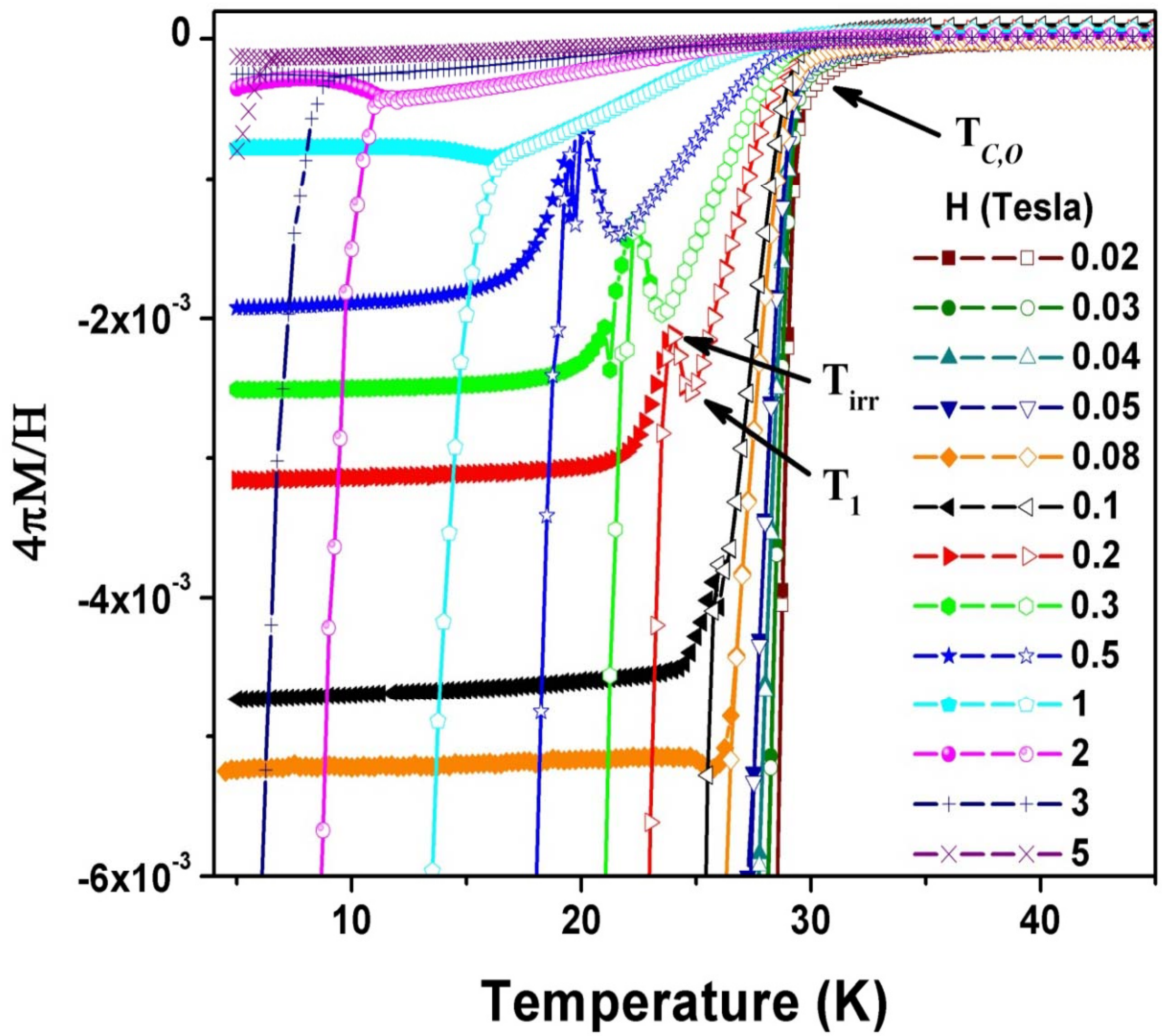


1. R. Gilardi et al., Eur. Phys. J. B47(2005)231
2. U. Divakar et al., PRL92(2004)237004

Our phase diagram is obtained based on SC diamagnetic transition of $La_{2-x}Sr_xCuO_4$ with x = 1/9

Obtain phase boundary in SC state

(I) T_{irr} and T_1 from raw data



$T_{C,O}$: onset T_C
T_{irr}: irreversible temperature
T_1: temperature where the linear part of M ends

T_{irr} and T_1 coincide below 0.1T and above 1T

Obtain phase boundary in SC state

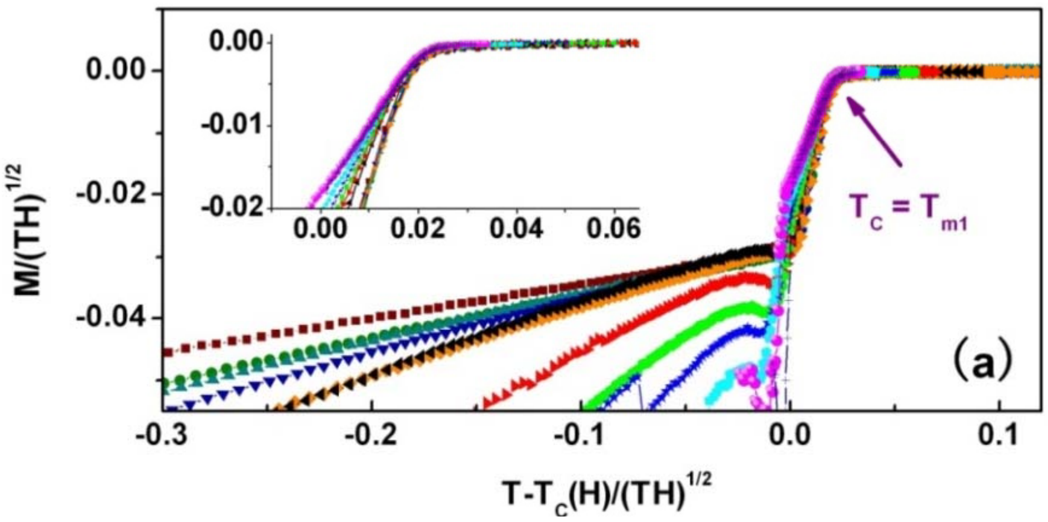
(II) 2D critical fluctuation fitting gives T_{m1} and T_{m2}

$$M/(TH)^{1/2} = F_2\left(A\frac{T-T_C(H)}{(TH)^{1/2}}\right)$$

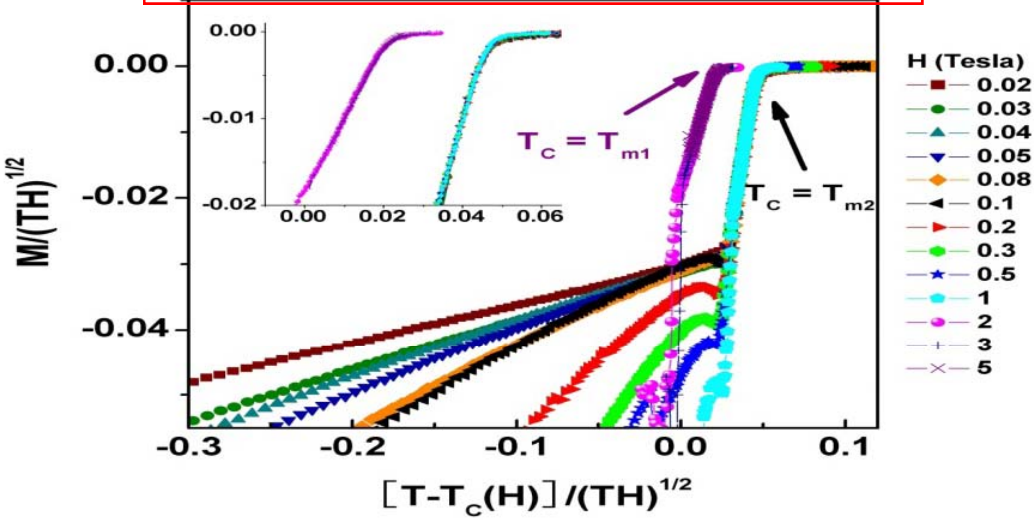
S. Ullah and A. T. Dorsey, PRL65(1990)2066;
U. Welp *et al.*, PRL67(1991)3180

Only works for intrinsic SC phase either at 1/9 doping or achieved by applied-field-tuning

Fitting onset region obtains T_{m1}

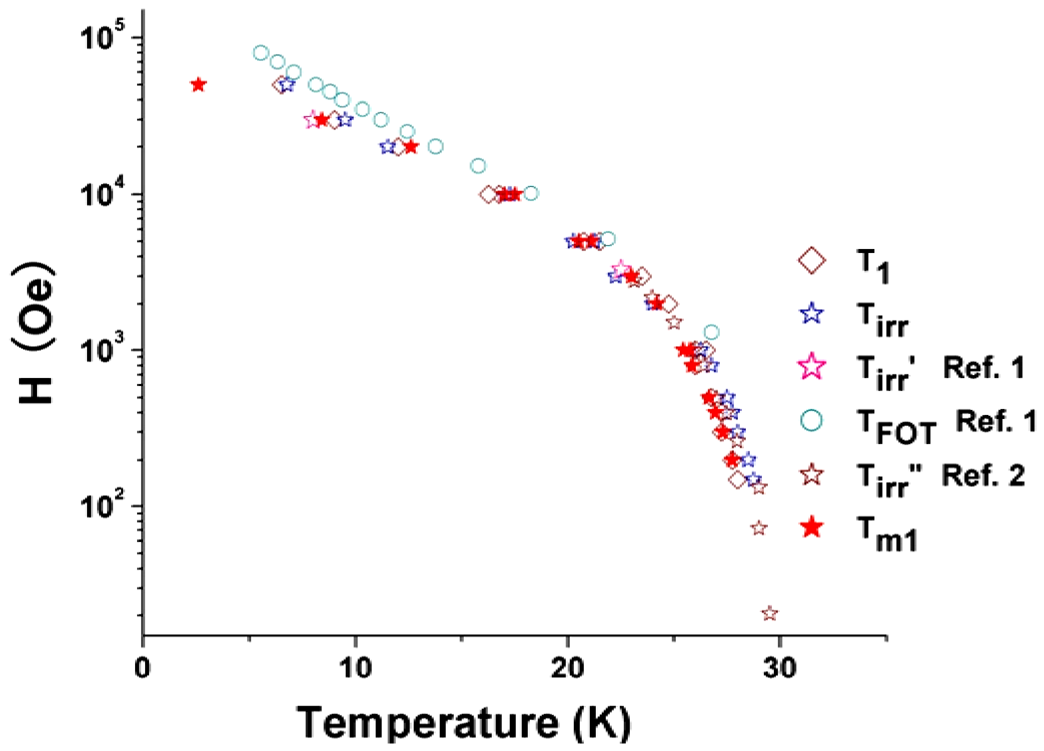


Fitting whole reversible region obtains T_{m1}(> 1Tesla), T_{m2} (< 1Tesla)



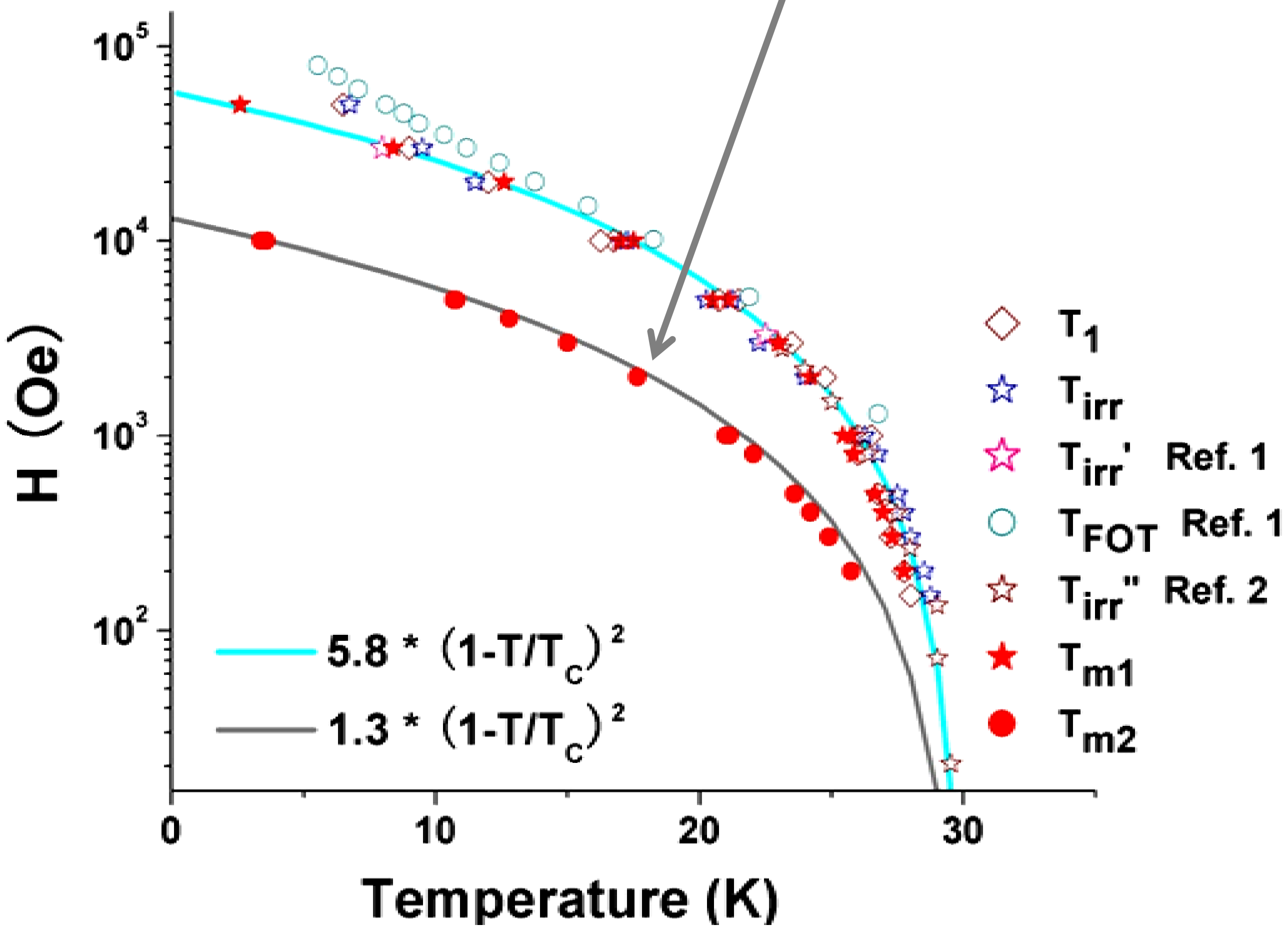
Phase boundary I- the vortex melting line

T_{m1} coincides with T_{irr}
the well-known
vortex melting line



Ref1. R. Gilardi et al., Eur. Phys. J. B47(2005)231
Ref2. U. Divakar et al., PRL92(2004)237004

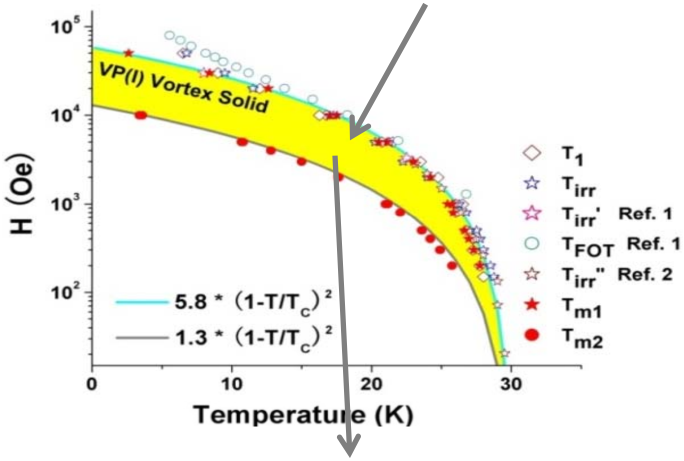
Phase boundary II: T_{m2} - a new phase boundary is found

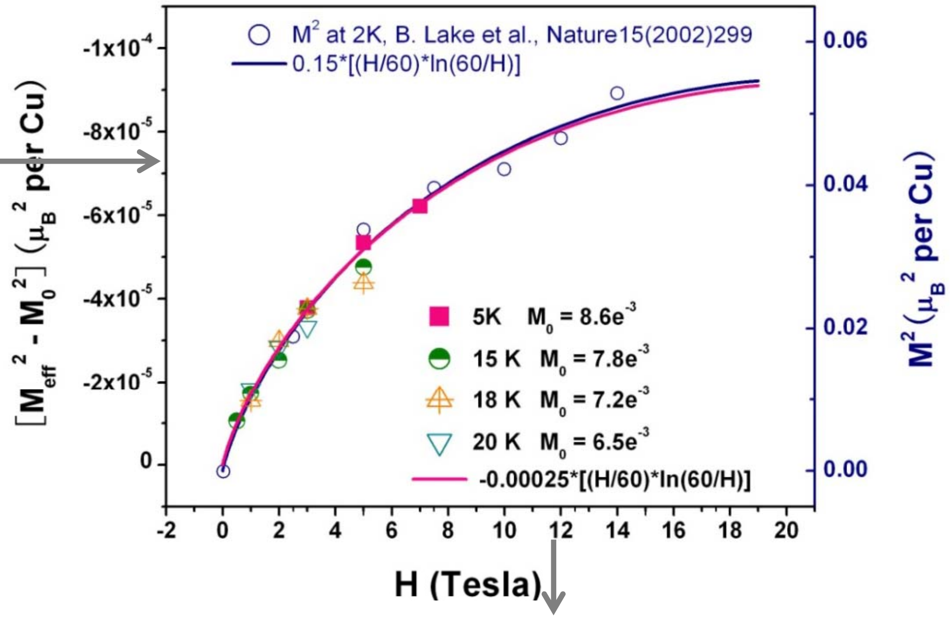


What does the new phase boundary imply?

New magnetic phase diagram –VP (I)

Demler-Sachdev-Zhang model (PRL2001) : for the coexistence of SDW&SC at QCP, the energy correction is field-dependent:
- $\nu[H/(H_{c2})*\ln(H_{c2}/H)]$





M_{eff}^2 : square of diamagnetic signal size in SC state

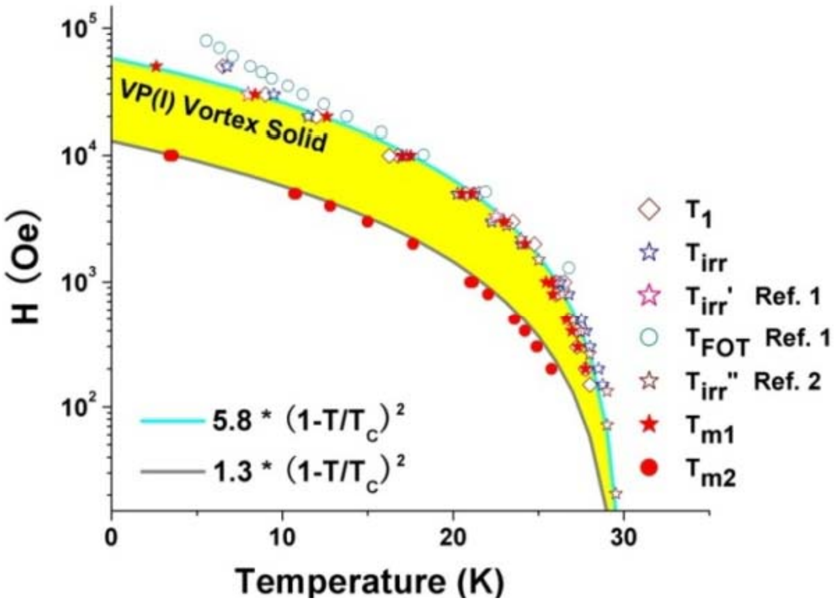
Between T_{m1} and T_{m2}:

$M_{eff}^2 = M_0^2 - \nu(H/H_{c2})*\ln(H_{c2}/H)$

Neutron data: **LSCO with p=0.1**

- M^2 (field induced ordered spin moment squared) quantitatively follows the H*ln(1/H) dependence.
- AFM order is found to competing with SC

New magnetic phase diagram –VP (I)



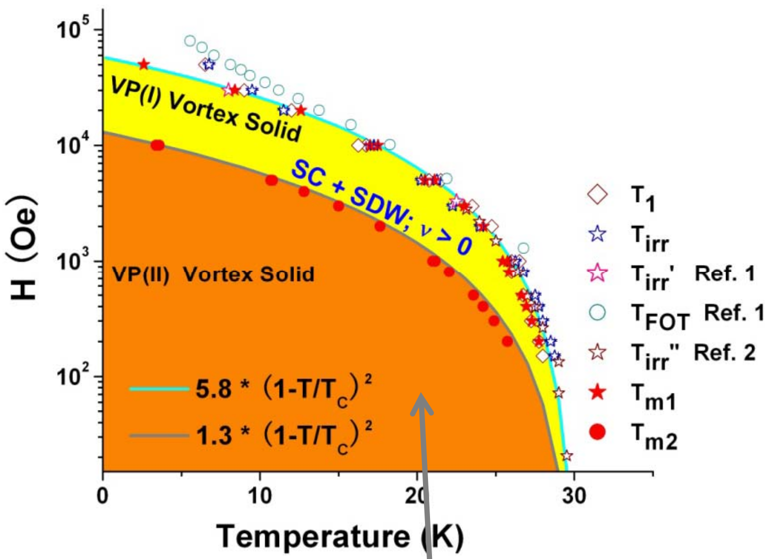
a **positive** $\nu = 0.00025$ indicates the SC & SDW are **competing,** the same as that of neutron results

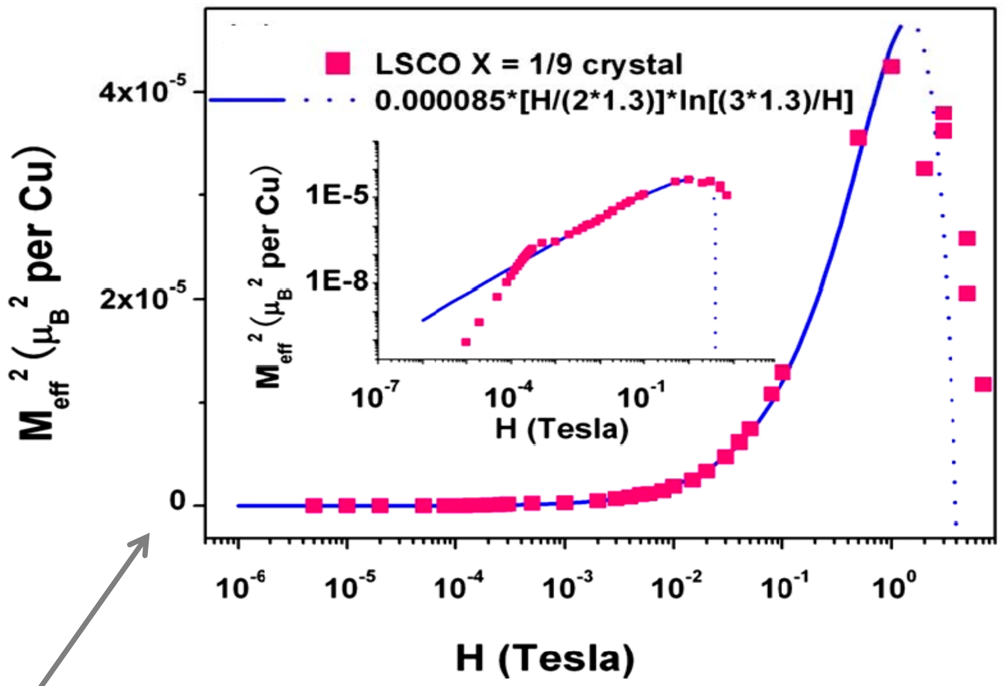
M_{eff}^2 : square of diamagnetic signal size in SC state

Between T_{m1} and T_{m2}:

$$M_{eff}^2 = M_0^2 - \nu (H/H_{c2}) * \ln(H_{c2}/H)$$

New magnetic phase diagram–VP (II)





Below T_{m2}, the same H*ln(1/H) dependence works (from 4 Oe to 10000 Oe) however with a negative coefficient ν -- the SC & SDW are **cooperating**

Below T_{m2}, the new phase boundary:

$M_{eff}^2 = 0-\nu(H/(2H_{c2}))*\ln(3H_{c2}/H)$

a **negative** ν = -0.000085 indicates the SC & SDW are **cooperating**

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Magic dopings ($1/4^n$) in LSCO: capacitance

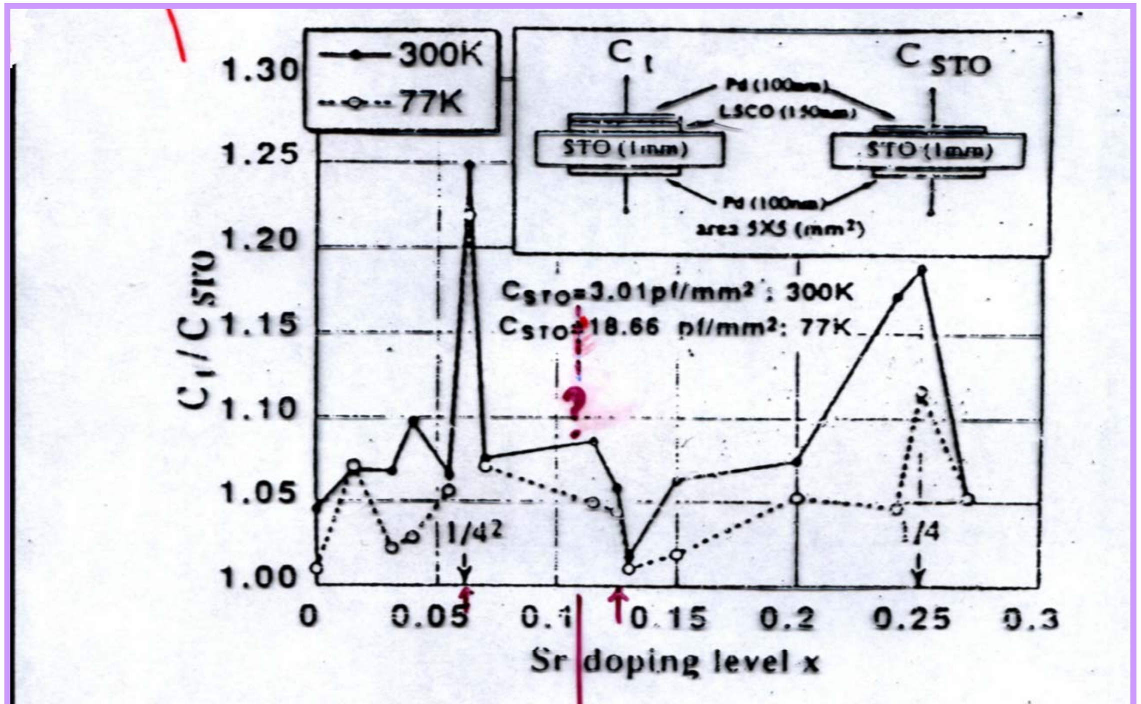


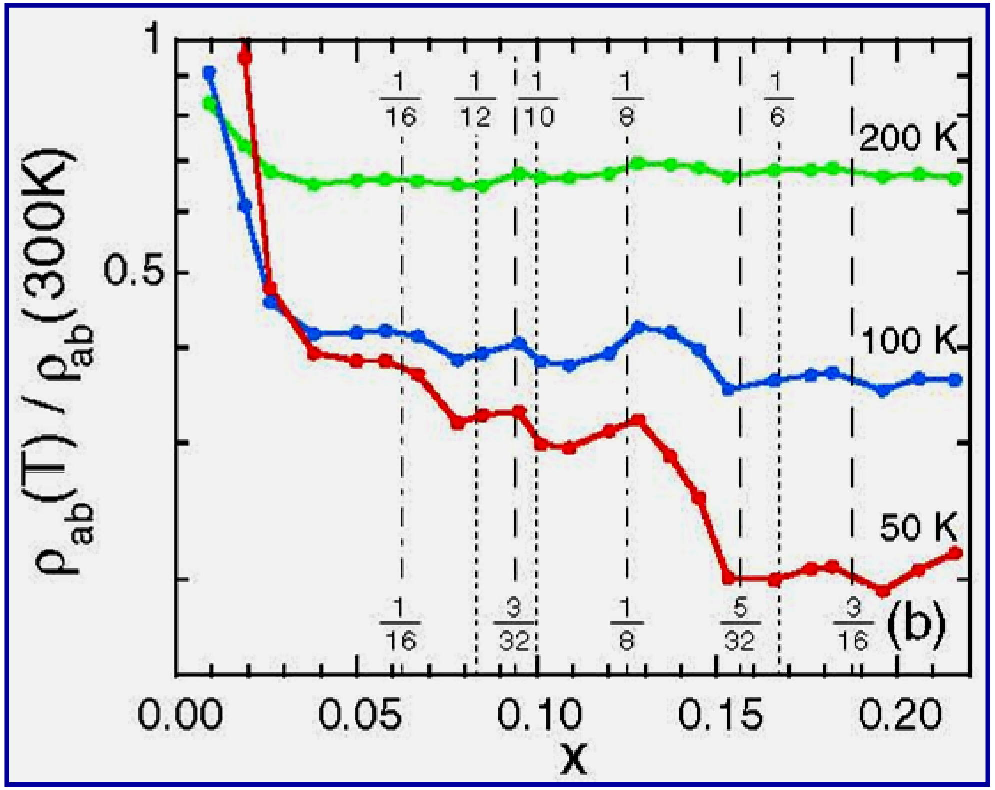
Fig. 1. The dependence of capacitance of a capacitor with double layer structure on the doping level x in $La_{2-x}Sr_xCuO_4$.

$La_{2-x}Sr_xCuO_4$ thin film

Sugahara et al., Jpn. J. Appl. Phys. 35 (1993) 1221

Magic dopings ($2m+1/2^n$) in LSCO: transport

Hole motion tends to be hindered at 0.06, 0.09, 0.13, 0.18 -- Tendency towards charge ordering at particular rational hole-doping fractions of 1/16, 3/32, 1/8 and 3/16

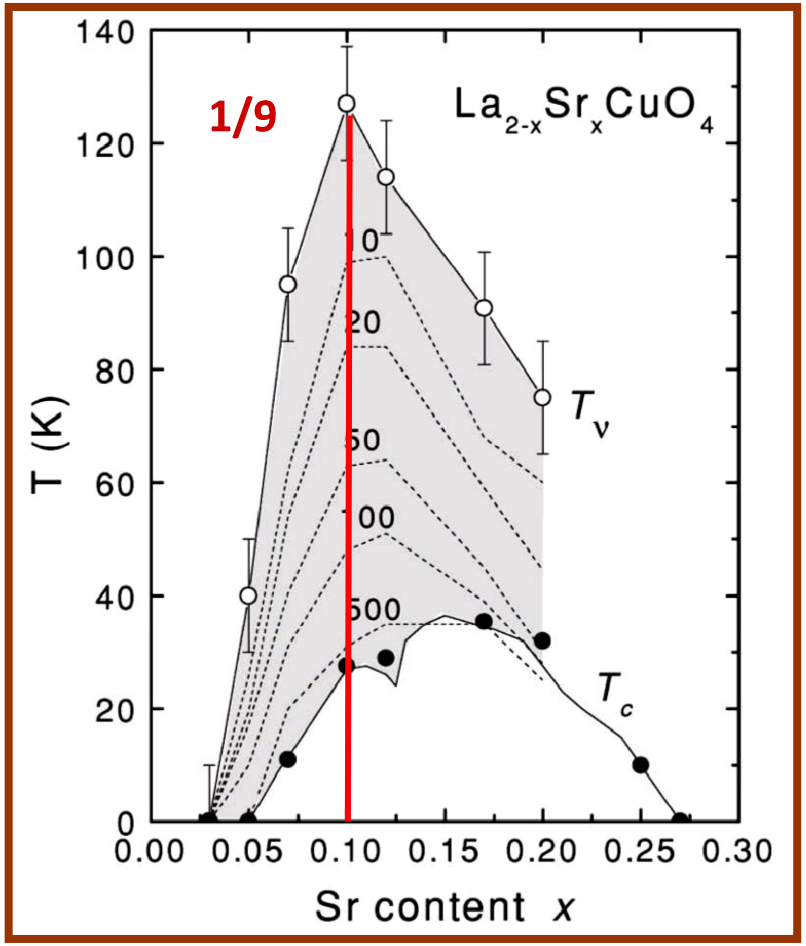


LSCO single crystals

S Komiya, HD Chen, SC Zhang and Y Ando, PRL94 (2005) 207004

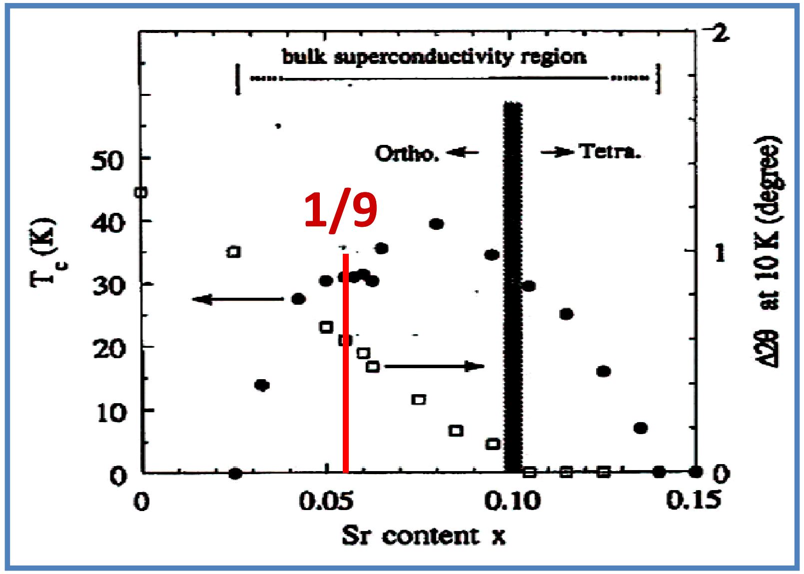
Magic dopings (1/9) in LSCO: onset T of Nernst signal

Onset temperature of SC fluctuation maximized at x = 0.1 ~ (1/9)

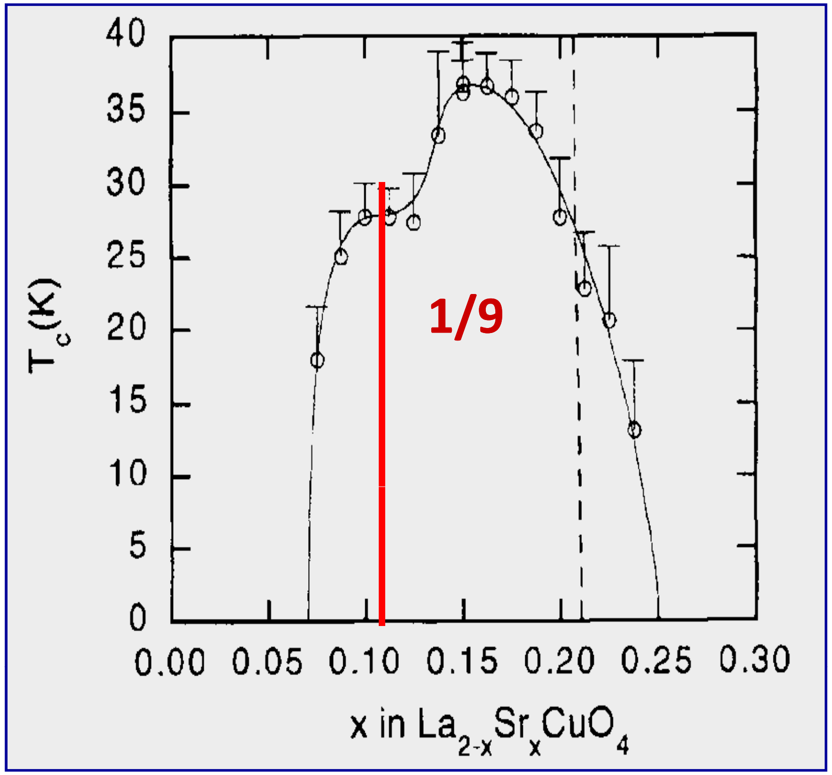


YY Wang et al, PRB64(2001)224519

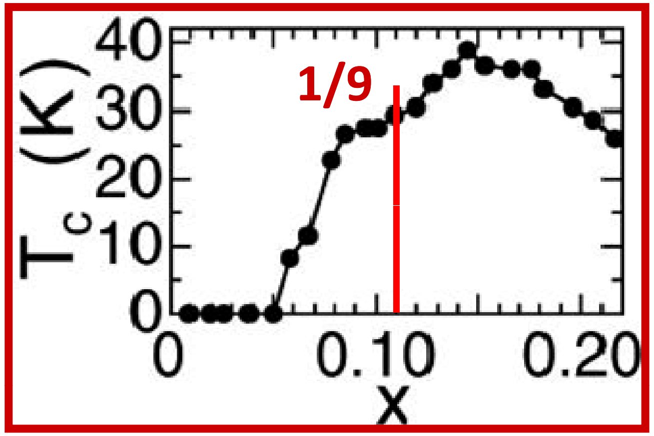
LSCO from different groups
Tc vs doping shows a platform around 1/9



LSCO polycrystals, T. Nagano *et al*. PRB48 (1993) 9689

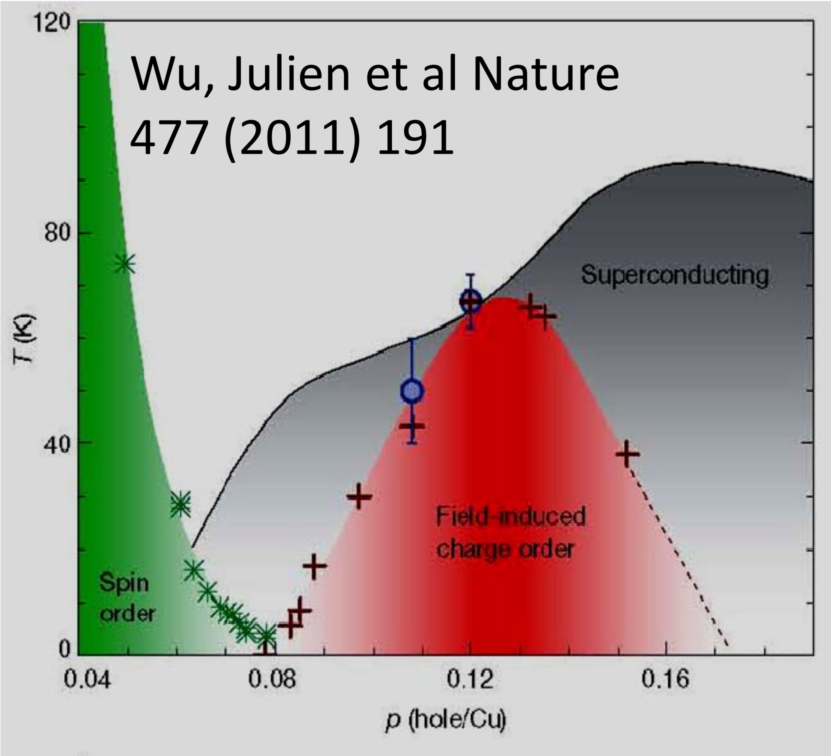


P.G. Radaelli et al., PRB 49 (1994) 4163

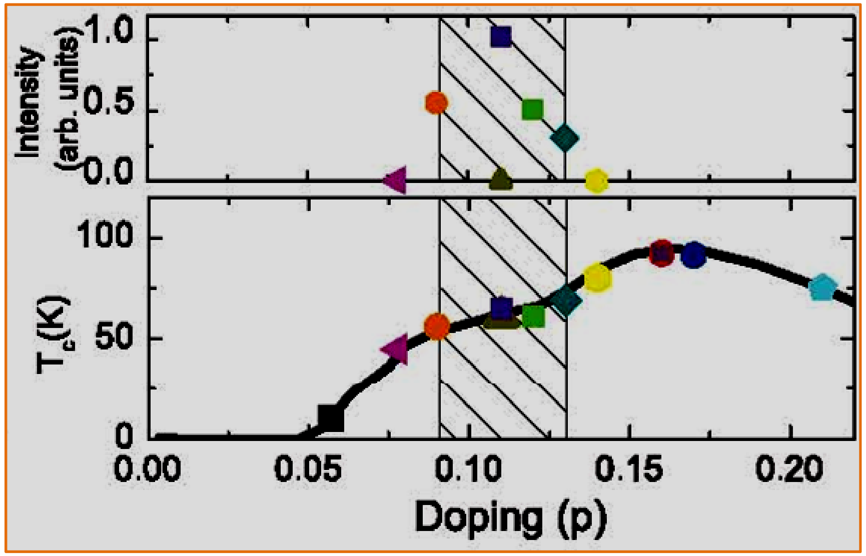


LSCO single crystals, **no 1/8 anomaly,** S. Komiya, H.D. Chen, S.C. Zhang, Y. Ando, PRL94(2005)207004

Magic dopings in other cuprates: YBCO



NMR: Field induced CDW in YBCO:
maximum T_{CO} at p~0.12

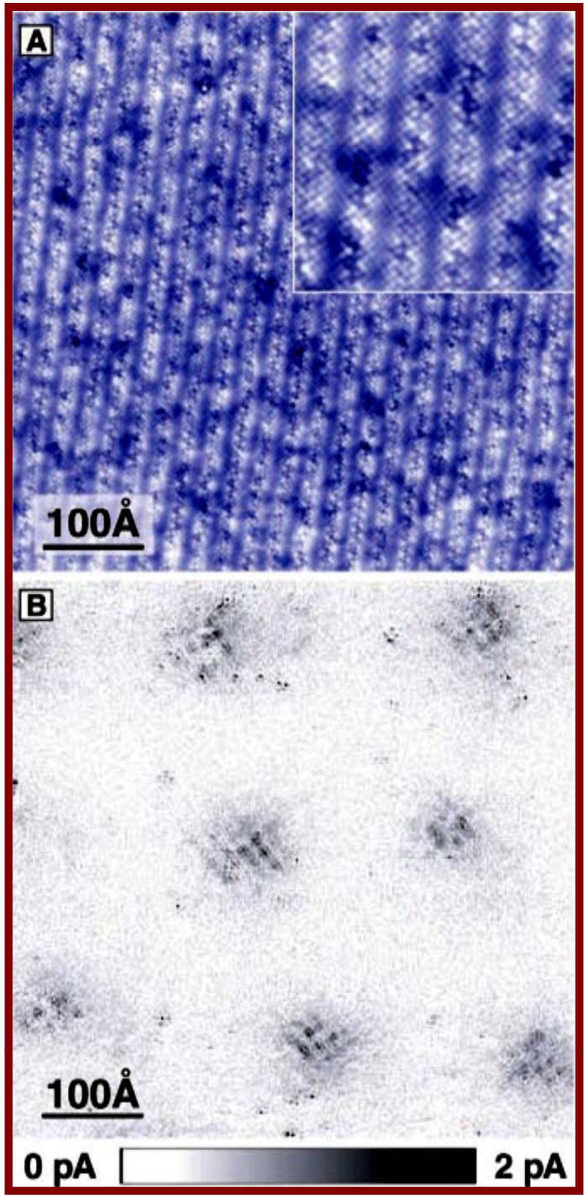


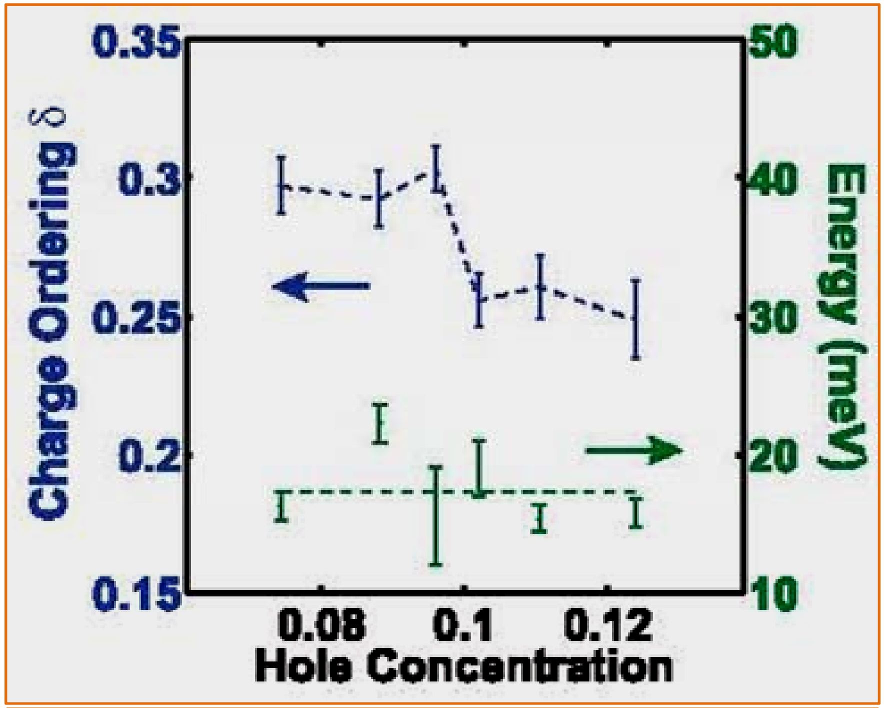
Resonant Elastic X-ray Scattering REXS: CDW intensity is maximum at p~0.11 in Y&NdBCO

Ghiringhelli, Keimer et al Science 337 (2012) 821

Magic dopings in other cuprates? STM - Bi2212

CDW in Bi2212





Wave vector Q changes from 1/4 to ~1/3 around **1/9**
E.H. Da Silva Neto, A. Yazdani et al., Science343 (2014) 393

4*4 lattice, Bi2212, J.E. Hoffman et al, Science 295 (2002) 466, confirmed by vortex-core spectroscopy, G. Levy et al, PRL95 (2005) 257005

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A collaboration with P.H. Hor & Y.H. Kim: ***J. Phys. 15 (2003) 8485***

Composite Charge Model (based on IR)

'Charge Lattice'

+

Coexisting Free-Carriers

a small fraction of free holes that move on the electronic lattice formed by the rest of the holes

Composite charge model well describes our observations, for examples :

- **the smallest Meissner signal size with sharp SC transition at magic doping of 1/9**
- **The presence of the collective modes (ωG) and small fraction of free holes (~0.2% of the total holes) from IR experiments**

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- The magic doping at 1/9 is missed in the most phase diagrams
- Intrinsic superconducting phases at magic dopings with p = 1/16 and 1/9 and their peculiar features
- Evidences from literatures support magic dopings at 1/16 and 1/9
- Composite charge model
- **Summary**

Summary

- There exist intrinsic electronic phases at magic dopings of 1/16 and1/9 in LSCO.
- Intrinsic SC phases exhibit peculiar features
- Intrinsic SC phase may have a pure d-wave SC gap
- We find a new phase boundary in SC phase diagram, below which the SC & SDW are cooperating while competing above
- Composite charge model is proposed : a small fraction of free holes that move on the electronic lattice formed by the rest of the holes

Thanks for your attention !